Branching Fraction Measurement of $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$
and Search for a Narrow Resonance with the Belle Experiment

Elisabeth Patricia Panzenböck

Georg-August University, Göttingen, Germany
Nara Women's University, Nara, Japan

Göttingen
December 2nd 2014
Contents

- Exotic Hadrons and Charmonium(-like) States
- The Belle Experiment
- Event Selection and Reconstruction of $B^\pm \rightarrow \chi_{c1}^{\pm} \pi^\mp \pi^\mp K^\pm$
- MC Studies and Results
  - Branching Fraction Measurement
  - Invariant Mass Spectrum of $\chi_{c1}^{\pm} \pi^\mp \pi^\mp$
- Conclusion
Why Exotic Hadrons?

- We see two types of conventional structures in hadrons: meson & baryon
Why Exotic Hadrons?

- we see two types of conventional structures in hadrons: meson & baryon
- other combinations are not explicitly forbidden by QCD!
  - new forms of matter such as mesonic molecules, tetraquarks, quark-gluon hybrids and others
- QCD motivated models for hadrons predict these exotic states in their calculations
Why Exotic Hadrons?

• we see two types of conventional structures in hadrons: meson & baryon

• other combinations are not explicitly forbidden by QCD!
  - new forms of matter such as mesonic molecules, tetraquarks, quark-gluon hybrids and others

• QCD motivated models for hadrons predict these exotic states in their calculations

• lack of experimental evidence for a long time, but many discoveries recently
  → unusual hadron structures might be a key to reveal a new aspect of QCD
Charmonium(-like) States

- light flavours ($u, d, s$) may mix, still interesting i.e. for glueball searches

- relation between observed states and constituent quarks is desired to be rather straightforward

- advantage of heavy flavours ($c, b$): higher masses serve as cut-off and allow usage of non-relativistic QCD to precisely calculate spectrum

$J$: angular momentum
$P$: parity
$C$: charge conjugation
Charmonium(-like) States

- light flavours ($u, d, s$) may mix, still interesting i.e. for glueball searches

- relation between observed states and constituent quarks is desired to be rather straightforward

- advantage of heavy flavours ($c, b$): higher masses serve as cut-off and allow usage of non-relativistic QCD to precisely calculate spectrum

- trends in the spectrum:
  - narrow states below open charm (DD) threshold, electromagnetic decays compete with hadronic decays (suppressed by OZI rule!)
Charmonium(-like) States

- light flavours \((u, d, s)\) may mix, still interesting i.e. for glueball searches

- relation between observed states and constituent quarks is desired to be rather straightforward

→ advantage of heavy flavours \((c, b)\): higher masses serve as cut-off and allow usage of non-relativistic QCD to precisely calculate spectrum

trends in the spectrum:
  - narrow states below open charm \((DD)\) threshold
  - broad states above threshold due to strong decay to charmed meson pair
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production

\[ J^{PC} = 0^+, 1^-, 1^{++} \]
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production

\[ J^{PC} = 0^+, 2^{++} \]
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production
Charmonium(-like) Production in B Factories

- various processes to produce charmonium(-like) particles
- allowed/favoured quantum numbers depend on production process

(a) B meson decays
(b) initial state radiation
(c) two-photon collisions
(d) double charmonium production

→ ideal clean environment for charmonium spectroscopy
The Discovery of X(3872)

- Belle, 2003: very narrow peak found above the D\bar{D} threshold in B' → (J/ψπ⁺π⁻)K⁺!
- does not match properties of known conventional charmonium states
  - are there other decay modes?
  - how is X(3872) related to D⁺D⁎ as it is very close to this threshold?
X(3872) Properties

- quantum numbers $J^{PC} = 1^{++}$ determined from angular distribution of $J/\psi \pi^+\pi^-$
- might be a conventional $c\bar{c}$ state, maybe the as yet unseen $\chi_{c1}(2P)$
X(3872) Properties

- quantum numbers $J^{PC} = 1^{++}$ determined from angular distributions of $J/\psi\pi^+\pi^-$ and $J/\psi(\pi^+\pi^-\pi^0)$
- isospin violation found in equally often decays to two pions via $\rho$ ($I=1$) and three pions via $\omega$ ($I=0$)
  - mass difference of 50 MeV to $\chi_{c1}(2P)$ and isospin violation disfavour assignment as conventional $c\bar{c}$!
- no partner found: charged or differing mass, suggests strong isospin 0 component, C-odd
  - isospin violation and lack of partner states disfavour tetraquark hypothesis according to model predictions!

\[
\frac{\mathcal{B}(X(3872) \to J/\psi\omega)}{\mathcal{B}(X(3872) \to J/\psi\rho)} = 1.0 \pm 0.4 \pm 0.3
\]

- charged partner search in $J/\psi\pi^+\pi^0$
- C-odd partner search in $J/\psi\eta$ and $\chi_{c1}\gamma$
- different mass search in charged vs. neutral $B$ decays

\[
\frac{\mathcal{B}(B^+ \to X(3872)K^+)}{\mathcal{B}(B^0 \to X(3872)K^0)} \sim 0.5
\]
X(3872) Properties

- Quantum numbers $J^{PC} = 1^{++}$ determined from angular distributions of $J/\psi \pi^+ \pi^-$ and $J/\psi (\pi^+ \pi^- \pi^0)$
- Isospin violation found in equally often decays to two pions via $\rho$ ($I=1$) and three pions via $\omega$ ($I=0$)
- No partner found: C-odd, charged or differing mass suggests strong isospin 0 component
- Mass $(3871.69 \pm 0.17)$ MeV is very close to the $D^0 D^{*0}$ threshold at $(3871.80 \pm 0.09)$ MeV!
- Decays to $D^0 D^{*0}$ have been observed with $\text{Br}(X(3872) \rightarrow D^0 D^{*0}) \approx 10 \times \text{Br}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$
  - Might be a $D^0 D^{*0}$ (di-mesonic) molecule
X(3872) Properties

- quantum numbers $J^{PC} = 1^{++}$ determined through angular distribution of $J/\psi\pi^+\pi^-$ and $J/\psi(\pi^+\pi^-\pi^0)$
- isospin violation found in equally often decays to two pions via $\rho$ ($I=1$) and three pions via $\omega$ ($I=0$)
- no partner found: C-odd, charged or differing mass suggests most likely isospin 0
- mass $(3871.69 \pm 0.17)$ MeV is very close to the $D^0\bar{D}^{*0}$ threshold at $(3871.80 \pm 0.09)$ MeV!
- decays to $D^0\bar{D}^{*0}$ have been seen with $\text{Br}(X(3872) \rightarrow D^0\bar{D}^{*0}) \approx 10 \times \text{Br}(X(3872) \rightarrow J/\psi\pi^+\pi^-)$
- **radiative decays**: measured opposite of prediction $\text{Br}(X(3872) \rightarrow \psi(2S)\gamma) \approx 2.5 \times \text{Br}(X(3872) \rightarrow J/\psi\gamma)$
- also: pure molecule would be too **fragile** to be produced at Tevatron (CDF) or LHC (LHCb)
  - disfavours pure molecule hypothesis!
Interpretation for $X(3872)$

- most plausible interpretation of $X(3872)$: admixture!
- $D\bar{D}$ molecule is mixing with an ordinary charmonium state with same $J^{PC}$,
  - i.e. the as yet unseen $\chi_{c1}(2P)$
- quantum numbers
- molecular part can explain isospin violation
- conventional $c\bar{c}$ core can explain the production in high energy machines like Tevatron or LHC

![Diagram showing branching fractions and predictions for pure $c\bar{c}$ and admixture models.]

$R_{\psi\gamma}$: ratio of branching fractions of $X(3872)$ decay into $\psi(2S)\gamma$ and $J/\psi\gamma$
Interpretation for $X(3872)$

- most plausible interpretation of $X(3872)$: admixture!
- $D\bar{D}$ molecule is mixing with an ordinary charmonium state with same $J^{PC}$, i.e. the as yet unseen $\chi_{c1}^{(2P)}$
- if $\chi_{c1}^{(2P)}$ is not mixing to form $X(3872)$, it is still expected to decay to $\chi_{c1}^{(1P)}\pi^+\pi^-$
  - $\chi_{c1}^{(2P)}$ mass prediction at 3920 MeV
  - $\chi_{c1}^{(2P)} \rightarrow \chi_{c1}^{(1P)}\pi^+\pi^-$ dipion transition expected due to no quantum number conflict, as seen in $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$
Interpretation for $X(3872)$

- most plausible interpretation of $X(3872)$: admixture!
- $D\bar{D}$ molecule is mixing with an ordinary charmonium state with same $J^{PC}$, i.e. the as yet unseen $\chi_{c1}^{(2P)}$
- if $\chi_{c1}^{(2P)}$ is not mixing to form $X(3872)$, it is still expected to decay to $\chi_{c1}^{(1P)}\pi^+\pi^-$
  - $\chi_{c1}^{(2P)}$ mass prediction at 3920 MeV
  - $\chi_{c1}^{(2P)} \rightarrow \chi_{c1} \pi^+\pi^-$ dipion transition expected due to no quantum number conflict, as seen in $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

in both cases: $\chi_{c1} \pi^+\pi^-$ is a suitable and interesting source to look for either $X(3872)$ or $\chi_{c1}^{(2P)}$!
The Belle Experiment

**KEKB:** 8 GeV e\(^-\) beam \(\times\) 3.5 GeV e\(^+\) beam mainly @ \(\Upsilon(4S)\) resonance (\(\sqrt{s} = 10.58\) GeV)

**Belle Detector:** high resolution 4\(\pi\) spectrometer with particle identification capability
Belle Detector Performance

4π general purpose spectrometer with

- high momentum resolution $\sigma_p/p = 0.3\%@1\text{GeV}/c$
- ability to detect photons down to 30 MeV
- good photon energy resolution $\sigma_M = 5\text{ MeV}$ for $\pi^0 \rightarrow \gamma\gamma$
- lepton identification capability $\epsilon > 0.9$, fake < 0.01
- K/π/ρ separation capability $\epsilon \sim 0.9$, fake < 0.1
- excellent B decay vertex reconstruction $\sigma(\Delta z) = 80\mu\text{m}$!
Belle Experiment Achievements

- Originally designed and operated to test SM mechanism for CP violation and measure time-dependent CP violation in the B system
- Run 1999 – 2010: 772M B meson pairs recorded
- All its features led to many discoveries, also beyond CP violation

Integrated luminosity of B factories

- World's highest luminosity in $e^+e^-$ at Y(4S) region!
Event Selection and Decay Reconstruction: $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$

- analysis procedure: reconstruct $B^\pm$
Event Selection and Decay Reconstruction: $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$

- analysis procedure: reconstruct $B^\pm$
  - dE/dx in CDC,
  - E/p ratio (E in ECL and p in CDC, SVD)
  - shower shape in ECL
  - number of Cherenkov photons in ACC
  - track penetration depth and hit scatter pattern in KLM
  - reconstructed hits in KLM compared to extrapolation of CDC tracks

- selection cuts for intermediate particles:
  - impact parameters: distance to interaction point for charged tracks
    $|dr| < 1.5 \text{ cm}, |dz| < 5.0 \text{ cm}$
  - electron likelihood $> 0.01$
  - muon likelihood $> 0.1$

- $\chi_{c1}$ decay:
  - $\chi_{c1} \rightarrow J/\psi \gamma$
  - $J/\psi \rightarrow e^+e^-$
Event Selection and Decay Reconstruction: $B^{\pm} \rightarrow \chi_{c1} \pi^+\pi^- K^{\pm}$

- analysis procedure: reconstruct $B^{\pm}$

- selection cuts for intermediate particles:
  - impact parameters: distance to interaction point for charged tracks $|dr| < 1.5$ cm, $|dz| < 5.0$ cm
  - electron likelihood $> 0.01$
  - muon likelihood $> 0.1$
  - $J/\psi$ window (nom. mass 3097 MeV): $2950/3030$ MeV $\leq M(e^+e^-/\mu^+\mu^-)$ $\leq 3130$ MeV
Event Selection and Decay Reconstruction: $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$

- analysis procedure: reconstruct $B^\pm$

  - selection cuts for intermediate particles:
    - **impact parameters**: distance to interaction point for charged tracks
      $|dr| < 1.5\text{ cm}$, $|dz| < 5.0\text{ cm}$
    - **electron likelihood**: $> 0.01$
    - **muon likelihood**: $> 0.1$
    - **$J/\psi$ window** (nom. mass 3097 MeV):
      $2950/3030\text{ MeV} \leq M(e^+e^-/\mu^+\mu^-) \leq 3130\text{ MeV}$
    - **$\chi_{c1}$ window** (nom. mass 3511 MeV):
      $3467\text{ MeV} < M(J/\psi \gamma) < 3535\text{ MeV}$
    - perform **mass-constrained fits** for $J/\psi$ and $\chi_{c1}$ candidates
Event Selection and Decay Reconstruction: $B^{\pm} \rightarrow \chi_{c1} \pi^{+}\pi^{-} K^{\pm}$

- **analysis procedure: reconstruct** $B^{\pm}$
  - kinematic variables in $\Upsilon(4s)$ rest frame:
  - beam-constrained mass $M_{bc}$ and difference to beam energy $\Delta E$
  
  \[
  M_{bc} = \sqrt{E_{\text{beam}}^2 - (p_{\chi_{c1}\pi\pi} + p_K)^2}
  \]
  \[
  \Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\text{beam}}
  \]

- **selection cuts for intermediate particles:**
  - impact parameters: distance to interaction point for charged tracks $|dr| < 1.5$ cm, $|dz| < 5.0$ cm
  - electron likelihood $> 0.01$
  - muon likelihood $> 0.1$
  - $J/\psi$ window (nom. mass 3097 MeV):
    - $2950/3030$ MeV $\leq M(ee/\mu\mu) \leq 3130$ MeV
  - $\chi_{c1}$ window (nom. mass 3511 MeV):
    - $3467$ MeV $< M(J/\psi \gamma) < 3535$ MeV
  - perform mass-constrained fits for $J/\psi$ and $\chi_{c1}$ candidates
Pion Selection

- small Q-value in $\chi(3872) \rightarrow \chi_{c1} \pi^+\pi^- : 
  3872 - (3511+140+140) \approx 80$ MeV
- pions have very low transverse momenta $p_T$
- results in curl up in CDC and possible duplicated reconstruction
- opening angle $\theta_{\text{open}}$ between pion tracks:
  - $\sim 0^\circ$ for same charge
  - $\sim 180^\circ$ for opposite charge
- compare pions in pairs, select the one with smallest distance to interaction point

$$\left| \frac{dr}{15\text{mm}} \right|^2 + \left| \frac{dz}{50\text{mm}} \right|^2$$

- $p_T < 0.25$ GeV
- $|p(\pi_1) - p(\pi_2)| < 0.1$ GeV
B Candidate Reconstruction
B Candidate Reconstruction

 ideally peaks at 0

nom. B mass at 5.279 GeV

\[ M_{bc} = \sqrt{E_{\text{beam}}^2 - (p_{\chi_{c1}\pi\pi} + p_K)^2} \]

\[ \Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\text{beam}} \]
B Candidate Reconstruction

- signal window cut:
  - $|\Delta E| < 0.02$ GeV
  - $M_{bc} > 5.27$ GeV

- nom. B mass at 5.279 GeV
- ideally peaks at 0
**ΔE Distribution – Background Estimation**

- $B \rightarrow J/\psi \times MC$ sample for bkg study
  - 100x amount of data

- **signal** is included in the MC sample

- only peaking background coming from $B^+ \rightarrow \chi_{c2} \pi^+\pi^+K^+$
  - shifted to negative $\Delta E$ region due to $\chi_{c2}$'s slightly higher mass, remember:
    $$\Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\text{beam}}$$

- all other backgrounds are smooth
ΔE Distribution – Background Estimation

- \( B \rightarrow J/\psi \times \text{MC sample for bkg study} \)
  - 100x amount of data

- **signal** is included in the MC sample

- only peaking background coming from \( B^+ \rightarrow \chi_{c2} \pi^+\pi^-K^+ \)
  - shifted to negative ΔE region due to \( \chi_{c2} \)'s slightly higher mass, remember:

  \[
  \Delta E = (E_{\chi_{c1}\pi\pi} + E_K) - E_{\text{beam}}
  \]

- all other backgrounds are smooth

"Image Courtesy: Vishal Bhardwaj"
ΔE Distribution – PDF and MC Expectation

- unbinned maximum likelihood (UML) fit to $B \rightarrow J/\psi \times$ MC sample to find probability density function (PDF)
  - **signal**: sum of two Gaussians
  - $B^\pm \rightarrow \chi_{c2} \pi^\mp \pi K^\pm$: sum of two Gaussians
  - **flat bkg**: 1st order Chebyshev polynomial

- expected peak yield for the as yet unseen decay $B^\pm \rightarrow \chi_{c1} \pi^\mp \pi K^\pm$: 1700 events
  - assuming $B(B \rightarrow \chi_{c1} \pi^+ \pi^- K) = B(B \rightarrow J/\psi \pi^+ \pi^- K) \cdot$ decay dynamics
ΔE Distribution – Looking at Data

first observation of the decay of $B^\pm \rightarrow \chi_c \pi^+ \pi^- K^\pm$ with a signal peak yield of $1597 \pm 76$ events

• comparing resolutions:
  $\sigma(\text{data}) / \sigma(\text{MC}) = (1.18 \pm 0.07)\%$
  → consistent within 10%
Reconstruction Efficiency Considerations

- efficiency is changing as a function of the invariant mass of $\chi_{c1} \pi^+\pi^-$
  - using a reconstruction efficiency weighted with the obtained signal yield per $\chi_{c1} \pi^+\pi^-$ mass bin
    \[
    \varepsilon = \frac{\sum_{i=1}^{10} \varepsilon(i) \cdot N_{\text{obs}}(i)}{\sum_{i=1}^{10} N_{\text{obs}}(i)}
    \]
- efficiency correction estimated from lepton and particle identification: 0.9622
  - resultant reconstruction efficiency 12.90%
Branching Ratio of $B^\pm \to \chi_{c1}\pi^+\pi^- K^\pm$

\[
B(B^+ \to \chi_{c1}\pi^+\pi^- K^+) = \frac{N_{\text{sig}}}{\varepsilon_{\text{det}} \times B(\chi_{c1} \to J/\psi \gamma) \times B(J/\psi \to \ell^+ \ell^-) \times N_{B\bar{B}}}
\]

- $N_{\text{sig}} = 1597 \pm 76$
- $N_{B\bar{B}} = 772 \times 10^6$
- $\varepsilon_{\text{det}} = 12.90\%$
- $\text{Br}(\chi_{c1} \to J/\psi \gamma) = (34.8 \pm 1.5)\%$
- $\text{Br}(J/\psi \to e^+e^-) = (5.94 \pm 0.06)\%$
- $\text{Br}(J/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06)\%$
- systematic uncertainty $= 5.10\%$

\[
B(B^+ \to \chi_{c1}\pi^+\pi^- K^+) = (3.89 \pm 0.19 \text{ (stat)} \pm 0.20 \text{ (syst)}) \times 10^{-4}
\]
The $\chi_{c1}^{\pi^+\pi^-}$ Invariant Mass Distribution

- select B signal region to look into $M(\chi_{c1}^{\pi^+\pi^-})$
  - $|\Delta E| < 0.02$ GeV
  - $M_{bc} > 5.27$ GeV

- search for
  - a narrow resonance $X(3872)$ at 3872 MeV or
  - an as yet unseen charmonium $\chi_{c1}^{(2P)}$ at 3920 MeV

![Graph showing the invariant mass distribution with selected regions for signal.]
M($\chi_{c1}$ $\pi^+\pi^-$) Distribution – Expected Background

- no peaking structure except for a $\psi$(2S) reflection at 4.1 GeV
- $\psi$(2S) → $J/\psi$ $\pi^+\pi^-$ + $\gamma$
- results in a fake $\chi_{c1}$!
- but: region above 4.0 GeV is not of interest for this analysis

Mbc > 5.27 GeV
$|\Delta E| < 0.02$ GeV
$B \rightarrow J/\psi X$ MC
$M(\chi_{c1} \pi^+\pi^-)$ Distribution – Looking at Data

- $M_{bc} > 5.27$ GeV
- $|\Delta E| < 0.02$ GeV
- 772M $\bar{B}B$ pairs
$M(\chi_{c1} \pi^+ \pi^-)$ Distribution – Looking at Data

$M_{bc} > 5.27$ GeV
$|\Delta E| < 0.02$ GeV
772M $B\bar{B}$ pairs
$X(3872) \rightarrow \chi_{c1} \pi^+ \pi^-$

- assuming $B(X(3872) \rightarrow \chi_{c1} \pi^+ \pi^-)$ to be similar to $B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$
- roughly 15 events expected and seeing $X(3872) \rightarrow \chi_{c1} \pi^+ \pi^-$ is within sensitivity reach
- not enough statistics for a conclusive fit
- use approach of Feldman-Cousins at 90% confidence level: estimated signal events $N_{\text{sig}} < 2.44$
- reconstruction efficiency $\varepsilon_{\text{det}} = 5.59\%$

$\mathcal{B}(B^\pm \rightarrow X(3872) K^{\pm}) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}(1P)\pi^+ \pi^-) < 1.4 \times 10^{-6}$ @ 90% C.L.
\[ \chi_{c1}(2P) \to \chi_{c1} \pi^+\pi^- \]

- natural width estimated from other \( \chi_{cJ}(2P) \) states \( \to 20 \) MeV
- resolution estimated from MC studies (Gauss standard deviation) \( \to 2 \) MeV
  \rightarrow \text{fit with convolution of Gauss and Breit-Wigner} \rightarrow (12.2 \pm 9.1) \text{ yield}
- considering 90% confidence level: estimated signal events \( N_{\text{sig}} < 30.34 \)
- reconstruction efficiency \( \varepsilon_{\text{det}} = 8.91\% \)

\[ \mathcal{B}(B^\pm \to \chi_{c1}(2P)K^\pm) \times \mathcal{B}(\chi_{c1}(2P) \to \chi_{c1}(1P)\pi^+\pi^-) < 1.1 \times 10^{-5} \text{ @ 90\% C.L.} \]
Conclusion

- $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$ unseen before this analysis and important to pinpoint $X(3872)$'s structure
- very interesting to look for: $X(3872)$ or $\chi_{c1}(2P)$ decaying to $\chi_{c1} \pi^+\pi^-$
- first observation of $B^\pm \rightarrow \chi_{c1} \pi^+\pi^- K^\pm$ with $(1597 \pm 76)$ signal events from 772M BB pairs dataset
  - branching fraction $3.89 \times 10^4$
- $\chi_{c1} \pi^+\pi^-$ invariant mass spectrum:
  - no statistically significant evidence for
    - either $X(3872)$: upper limit $1.4 \times 10^6$
    - nor $\chi_{c1}(2P)$: upper limit $1.1 \times 10^5$
Backup
Baryons are red-blue-green triplets

\[ \Lambda = u s d \]

Mesons are color-anticolor pairs

\[ \pi = \bar{u} d \]

Other possible combinations of quarks and gluons:

**Pentaquark**

\[ S = +1 \]

Baryon

**H di-Baryon**

Tightly bound 6 quark state

**Tetraquark**

Tightly bound diquark & anti-diquark

**Molecule**

loosely bound meson-antimeson “molecule”

**Glueball**

Color-singlet multi-gluon bound state

**q\bar{q} -gluon hybrid mesons**
Status on Exotic Hadrons

- unexpected and still-fascinating $X(3872)$ has been joined by more than a dozen other “XYZ” states that appear to lie outside the quark model

- charmonium(-like) states:
  - $X(3915), Y(3940), X(3940), X(4160)$
  - $Y(4260), Y(4360), Y(4660)$
  - $Z^+(3900), Z^+_1(4050), Z^+_2(4250), Z^+(4430)$

charged states aligned according to best guess at quantum numbers of neutral charged partner
Status on Exotic Hadrons

- unexpected and still-fascinating X(3872) has been joined by more than a dozen other “XYZ” states that appear to lie outside the quark model
  - charmonium(-like) states:
    - X(3915), Y(3940), X(3940), X(4160)
    - Y(4260), Y(4360), Y(4660)
    - Z(3900), Z(4050), Z(4250), Z(4430)
  - also, bottomonium(-like) states:
    - Z(10610) and Z(10650) as B(*)B*0 molecule candidates
    - equivalent to Y(4260) at 10.89 GeV?
Charmonium vs. Bottomonium – Status in PDG
On the origin of the narrow peak and the isospin symmetry breaking of the X(3872)

Sachiko Takeuchi\textsuperscript{1,4}, Kiyotaka Shimizu\textsuperscript{2}, and Makoto Takizawa\textsuperscript{3,4}

\textsuperscript{1}Japan College of Social Work, Kiyose, Tokyo 204-8555, Japan
\textsuperscript{2}Department of Physics, Sophia University, Chiyoda-ku, Tokyo 102-8554, Japan
\textsuperscript{3}Showa Pharmaceutical University, Machida, Tokyo 194-8543, Japan
\textsuperscript{4}Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198, Japan
*E-mail: s.takeuchi@jcsw.ac.jp

19/8/2014

The $X(3872)$ formation and decay processes in the $B$-decay are investigated by a $c\bar{c}$-two-meson hybrid model. The two-meson state consists of the $D^0\bar{D}^*0$, $D^+D^{*-}$, $J/\psi\rho$, and $J/\psi\omega$ channels. The energy-dependent decay widths of the $\rho$ and $\omega$ mesons are introduced. The $D\bar{D}^*$ interaction is taken to be consistent with a lack of the $BB^*$ bound state. The coupling between the $D\bar{D}^*$ and $J/\psi\rho$ or the $D\bar{D}^*$ and $J/\psi\omega$ channels is obtained from a quark model. The $\bar{c}\bar{c}-D\bar{D}^*$ coupling is taken as a parameter to fit the $X(3872)$ mass. The spectrum is calculated up to 4 GeV.

It is found that very narrow $J/\psi\rho$ and $J/\psi\omega$ peaks appear around the $D^0\bar{D}^{*0}$ threshold. The size of the $J/\psi\pi^+$ peak we calculated is 1.29-2.38 times as large as that of $J/\psi\pi^2$. The isospin symmetry breaking in the present model comes from the mass difference of the charged and neutral $D$ and $D^*$ mesons, which gives a sufficiently large isospin mixing to explain the experiments. It is also found that values of the ratios of the transfer strengths can give the information on the $X(3872)$ mass or the size of the $c\bar{c}-D\bar{D}^*$ coupling.
**X(3872) as Admixture**

The density of each component differs as a function of the distance $r$ from the object's center!
Belle Subdetectors

- The Belle detector consists listed in order of radial distance from the interaction point of
  - a six-layer silicon vertex detector (SVD2),
  - a ~50-layer central drift chamber (CDC),
  - an array of ~1200 aerogel Cherenkov counters (ACC),
  - ~130 time-of-flight scintillation counters (TOF),
  - an electromagnetic calorimeter containing 8736 CsI(Tl) crystals (ECL),
  - and the KLM detector.
- All but the KLM are contained in a superconducting solenoid with a central magnetic field of 1.5 T. The fourteen ~5-cm thick iron absorber plates of the KLM also serve as the solenoid’s return yoke.
Systematic Uncertainties

- **PDF** – 2.96%: modeling and set parameters used for fitting distributions
- **pion ID** – 1.96%: Estimations are made based on a $D^{*+} \rightarrow D^0(K^-\pi^+)\pi_{slow}$ process.
- **lepton ID (e, μ)** – 1.77%: $J/\psi \rightarrow e^+e^-$ (for EID) and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (for muID)
- **tracking** – 1.71%: Track finding efficiency has been measured by the number of partially and fully reconstructed $D^*$ decays in $D^* \rightarrow \pi D^0$, with $D^0 \rightarrow \pi\pi K_S$ and $K_S \rightarrow \pi^+\pi^-$. By calculating the ratio of tracking efficiency in data and MC, the systematic uncertainty associated with tracking has also been evaluated.
- **2ndary BF** – 1.50%
- **$N_{BB}$** – 1.37%: official number of Bs from Y(4S) recorded by Belle ($771.581 \pm 10.566) \times 10^6$
- **kaon ID** – 1.23%: see pion ID
- **$\pi^0$ veto** – 1.22%: obtaining the ratio of $\Delta E$ signal yield when using the cut, and without using the cut, for data and Monte Carlo, and then dividing those in a double ratio, $R(data/MC)$
- **signal MC** – 0.52%: limited MC sample of 0.5M events used to calculate efficiency

→ **total: 5.10%**
Electron Identification (EID)
EID Efficiency

- One can also obtain the EID efficiency or inefficiency by comparing the $J/\psi \rightarrow e^+e^-$ yield for the cases one or two electrons are tagged, or the difference of the two cases.
- The signal yield for single tagging and the difference between single- and double-tagged events can be translated to an (in)efficiency which is consistent with the inefficiency that is predicted by the MC.
- The EID efficiency expected from the generic hadronic MC is consistent with that for single electrons in real hadronic data within 1%. The EID inefficiency is verified to be consistent between data and MC within a 1.4% uncertainty.
EID Fake Rate for Pions and Kaons

- Inclusive $K_s \to \pi^+\pi^-$ decays are used as a source of charged pions to measure the EID fake rate. No requirement is placed on the pion used to test the EID routines.

- The overall agreement between data and MC is good in the pion fake rate case.

- The fake rate for $K^\pm$ is examined using the decay chain $D^{*+} \to D^0 (\to K \pi') \pi'$. The strategy for evaluating the fake rate is to compare the signal yield of $D^0$ with and without applying EID for the kaons.

- Comparing events without EID and events after applying EID and taking the ratio, the fake rate for the kaons is measured to be comparable to the MC prediction.

Fake rate = 
\[
\frac{\text{# of non-}e^\pm \text{ tracks found by tracking with the } L_{\text{eid}} > 0.5}{\text{# of non-}e^\pm \text{ tracks found by tracking}}
\]
Muon Identification (MuID)

- Muon identification begins with the reconstruction of a charged track in the CDC with matching SVD hits, and continues with its extrapolation through the outer detectors to its stopping point or its escape from the detector.

- A track is considered to be within the KLM acceptance if it crosses at least one RPC layer; this requires at least 0.6 GeV/c of momentum.

- A helical track, reconstructed in the CDC, is refined by a Kalman filter to determine the helix parameters near the outermost layer of CDC. The helix parameterization is justified by the uniformity of the solenoidal magnetic field within the tracking volume and the small energy loss of the track within the CDC.

- Muon Likelihood: Two quantities are used to test the hypothesis that a track is a muon rather than a hadron
  - the difference between the measured and expected range of the track
  - the goodness of fit of the transverse deviations of all hits associated with the track (normalized by the number of hits)
MuID Efficiency

- High-purity muons are obtained with the two photon reaction, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ by tagging one of the muons with a high muon likelihood and then examining the other minimum-ionizing track in the event.

- The contamination is predominantly from $e^+e^- \rightarrow \tau^+\tau^-$ where one $\tau$ decays leptonically to give a tag muon and the other decays to $\pi\nu$ to give a fake-muon candidate, or from $e^+e^- \rightarrow e^+e^-\pi\pi X$ where one of the pions is falsely tagged as a muon.

- The systematic uncertainty is estimated to be 2%, mainly from the residual hadron contamination in the muon sample.

Fig. 9. Measured efficiency of muon identification as a function of momentum, measured by $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$: (a) barrel ($51^\circ < \theta < 117^\circ$), (b) whole polar angle region ($25^\circ < \theta < 145^\circ$), for $L_\mu > 0.9$ (closed circles) and $L_\mu > 0.1$ (open circles).
MuLD Fake Rate for Pions and Kaons

- The majority of fake muons are punch-through or decay-in-flight pions and kaons.
- We measure the fake rate using the pions from $K_S \rightarrow \pi^+\pi^-$ and the kaons from $D \rightarrow K\pi$ where the D meson is identified by observing the slow pion in $D^* \rightarrow D\pi_{slow}$.
- A muon identification algorithm is used that uses the difference of muons from hadrons in the range and the scattering of the particles in the KLM.
- Fake rates of pions are approximately constant in the region $p > 1.5$ GeV/c. Fake rates of kaons are approximately constant in momentum above threshold.

Fig. 14. Measured fake rate of pions vs. momentum by $K_S \rightarrow \pi^+\pi^-$: (a) barrel, (b) whole polar angle region, for $L_\mu > 0.9$ (closed circles) and $L_\mu > 0.1$ (open circles).
$X(3872) \to \chi_{c1} \pi^+\pi^- -$ PDF and MC Expectation

$M_{bc} > 5.27 \text{ GeV}$

$|\Delta E| < 0.02 \text{ GeV}$

MC, normalized to exp. data statistics + generated signal

if there are 15 events of $X(3872) \to \chi_{c1} \pi^+\pi^-$
MC Study for $\chi_{c1}(2P)$

$B^\pm \rightarrow \chi_{c1}(2P)K^{\pm}$

$\sigma = 2$ MeV
The Belle2 Experiment

- Experimental Challenges
  - 10-20 times higher beam-related backgrounds: Pile-up noise, Radiation damage,
  - 10 times higher event rate: Seamless data acquisition system, High level intelligent trigger
  - Improved performance: Vertex reconstruction, High particle ID capability, Hermetic coverage.
The Belle2 Experiment

Image Courtesy: Ichiro Adachi (KEK)  
The Belle2 Experiment

- currents x2
- design luminosity of $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ → around 50 times as large as peak luminosity achieved by the KEKB collider
- large crossing angle → low-emittance “nano-beam” collisions (10μm x 60nm)
- vertex detector even closer to IP, 2 layers DEPFET pixel (14 & 22mm) sensors and 4 layers of DSSD
- CDC: larger radius and smaller cell size
- Time-Of-Propagation (TOP) counters: ring-image of Cherenkov light cones in quartz radiator bars, another ring-imaging Cherenkov counters with aerogel radiator in the forward end-cap
- ECL with wide dynamic range → 20 MeV to 7 GeV, 2MHz wave-form sampling readout → more robust against bkg, pure CsI crystals for end-cap → shorter time constant
- KLM modules will be replaced in the 2 innermost barrel layers and completely in the endcap
- Trigger rate 500Hz → 30kHz, Event size 40kB → 300kB(max)